When are two hands better than one?
A Study of Bimanual Interaction

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To my parents

Abstract

In everyday life people skillfully use both hands in complex tasks such as driving a car or drawing a picture. However, when attempting tasks on a computer, we are normally restricted to using our dominant hand for direct manipulation. Bimanual interaction is the study of how systems can be developed to allow users to take advantage of their capacity for skilled bimanual interaction.

Four design principles for developing bimanual interaction systems are distilled from a review of the current research. Principle One discusses the importance of understanding how people perform bimanual actions. Principle Two discusses what type of devices and actions should be used. Principle Three describes how bimanual interaction techniques can be used to eliminate modes. Principle Four discusses how bimanual interaction techniques can be used to increase usable screen space and reduce time to target and attention switching.

The principles are used to develop two systems (Bi-DM and Bi-Draw). These systems are evaluated with their equivalent traditional unimanual systems (Uni-DM and Uni-Draw). Bi-DM was slightly faster than Uni-DM though the difference was just outside the 95% significance level. Bi-Draw was significantly slower than Uni-Draw. The users were required to complete the tasks approximately. An experiment with an expert user of Bi-Draw showed that similar times to Uni-Draw can be achieved.

These results disagreed with prior work that showed bimanual interaction systems are more efficient than their equivalent unimanual versions. A third experiment based on earlier work was conducted. The users were required to complete tasks with a high accuracy level. Comparing the results from this experiment to the one on which it was based indicates that the low quality of the non-preferred mouse was probably responsible for the poor performance of our bimanual systems. Other likely factors detrimentally affecting the bimanual results include the low accuracy required for completing the tasks and the short training periods.

The thesis reveals that designing and implementing bimanual interfaces is susceptible to many subtle flaws. Without long training periods and well designed interfaces, bimanual systems are unlikely to reveal efficiency enhancements.

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Chapter I

Introduction

From eating breakfast to playing sport, from writing a grocery list to painting a work of art, we naturally use *both* hands in everyday life. Humans are exceptionally well skilled at coordinating both hands to perform complex tasks, yet when interacting with computers, we are often restricted to using only our dominant hand. The study of bimanual interaction investigates how these highly skilled actions can be used to improve human-computer interaction (HCI).

1.1 Area of Research

Bimanual interaction is concerned with how humans use both hands to accomplish tasks in everyday life and how those skills can be used to enhance HCI. To successfully use these skills on computers, users need to be given interfaces which facilitate bimanual interaction, devices that give appropriate affordance as to how they are to be used, and the designers of these systems need solid models of how humans act bimanually.

There are two types of bimanual action: symmetric, where each hand performs similar subtasks; and asymmetric, where each hand performs different but connected subtasks. Parallelism occurs when both hands are performing tasks at the same time. The amount of parallelism can vary, depending on how much work each hand is doing.

1.2 Research Contributions

A review of research into bimanual interaction was undertaken to determine the current knowledge of the field. From this review, it was noticed that while there are a number of prototype systems, few have been formally evaluated.

These systems were designed with various aspects of bimanual interaction in mind, yet there are no guidelines or principles for developing such systems. This lack of principles has lead to some research being conducted with poorly designed interaction techniques.

A set of four design principles was distilled from the review. These principles were used to design two systems (Bi-DM and Bi-Draw) which where evaluated with their equivalent unimanual systems. The evaluation showed the Bi-DM to be faster than its unimanual equivalent, but not significantly so. Bi-Draw was significantly slower than its unimanual equivalent.

These results disagree with prior work. Four explanations were proposed: that the poor quality of the non-preferred mouse degraded the performance of the bimanual systems (H1); that accuracy requirement of the tasks was too low (H2); that the amount of training provided was insufficient (H3); and that the implementation of the bimanual systems suffered from subtle flaws (H4). An expert evaluation was run using Bi-Draw and its unimanual equivalent to test H3. Even with long training, the times where similar. This suggested that while training was a factor, other explanations must be considered. A third experiment was conducted to test H1 and H2. This experiment was based on that of Leganchuk, Zhai and Buxton [39]. The results from the third experiment disagreed with the original work, suggesting that there was a fault with the experimental setup for our first two experiments. This result supports the explanation that the poor quality of the non-preferred mouse biased the experiments against the bimanual systems.

1.3 Thesis Overview

Chapter 2 presents a review of prior work on or relevant to bimanual interaction. This includes areas such as input devices and immersive virtual reality. Chapter 3 presents the four design principles for bimanual interaction. Chapter 4 discusses the two bimanual systems developed with the principles and their unimanual (one-handed) equivalent. Chapter 5 presents three experiments, two evaluating the systems developed and the third investigating explanations for the results from the first two experiments. Finally, Chapter 6 presents the conclusions and further work.

Chapter II

A Review of Bimanual Interaction

This chapter presents a review of bimanual interaction. The review is divided into four sections; Systems; Input Devices; Modelling; and Evaluations. The first investigates how bimanual interaction can be used by or influence systems and input metaphors. The second discusses input devices available for use with either the non-dominant or both hands. The third presents research into how humans interact bimanually and how this can be used to develop bimanual systems that accurately mimic human bimanual behaviour. The forth presents evaluations of theories and techniques of bimanual interaction.

2.1 Systems

The goal of current research is to produce bimanual interaction systems that are easier to use. This section discusses 2D systems, 3D systems and input metaphors that use bimanual interaction to increase their usability. The 2D systems category discusses systems based on either traditional unimanual systems, or real world tasks that are 2D, such as drawing. The 3D systems category discusses systems that are representations of a 3D world or tasks.

2.1.1 2D Systems

Some systems allow bimanual interaction as a side effect of their design objectives. Videoplace [36] is one such system. It allows users to interact with a virtual environment by projecting a live video image of the user onto a screen. The user is then able to interact with artifacts present in the screen. Another system that was not designed to use bimanual interaction is Marcel

[43]. Marcel is a physical desk that allows computer- and paper-based documents to be integrated into a single system. Two applications were developed for Marcel: a calculator able to read numbers from paper, and a French to English translator which displays the English translation of a French word. The user can select either numbers for the calculator or words for the translator simply by pointing to them on any document on the desk; the result is then projected onto the desk from above. The user is able to interact with all the documents on the desk with both hands.

Two systems that are redesigns of unimanual systems are CPN2000 [8] and Alias Wavefront's T3 [38]. CPN2000 is a system for editing and simulating coloured petri nets. Its design is based on toolglasses [10, 11] (see Section 2.1.3), marking menus and bimanual interaction. T3 is a drawing system designed with three design goals: maximise the amount of screen used for the artwork; avoid forcing the user to divert their visual attention from the artwork; and increase the degrees of manipulation and comfort of input. These goals were accomplished with the use of tablets, two-hands and transparency (hence T3). Both systems use toolglasses and bimanual manipulation of objects and the canvas.

One aspect of research into bimanual interaction encourages the design of applications from the user's point of view. Once an interaction is considered in terms of how it is done in the real world, designers are encouraged to duplicate that interaction in as much detail as possible. This technique has been applied to tape drawing by Balakrishnan, Fitzmaurice, Kurtenbach and Buxton [2]. In the automotive industry, tape drawing uses photographic tape to create 1:1 scale drawings of cars. This is achieved by unrolling the tape with one hand and sliding the other hand along the tape to fasten it to the drawing board. Balakrishnan et al. were able to replicate the techniques used by the artists. The drawing board was represented by a projected display on a large screen. The artists would stand in front of the screen and interact with the system as they would a drawing board. One device represented the roll of tape while another was used to "fasten" the tape to the display. Artists were able to use the system with under a minute of instruction. Balakrishnan et al. were able to use these techniques to successfully implement a computerised version of tape drawing. This system was extended to investigate 3D interaction techniques for large displays [25]. As the 2D tape drawings form the basis of the 3D model, the new system allows the designers to see the effects of updates on the 2D projections to the 3D model.

To fully explore bimanual interaction systems, programming environments designed to support bimanual interaction systems are also needed. MMM [12] is such a software architecture. It is designed to develop multi-user programs allowing users to operate at the same time on the same screen. This setup also allows the development of systems with multiple input devices on one computer. Chatty [17, 18] made extensions to the Whizz graphical toolkit to allow the development of bimanual systems and discusses relevant issues experienced in creating those extensions. Groupkit [49] was used to develop the bimanual systems in Chapter 4.

2.1.2 3D Systems

Immersive Virtual Reality and 3D desktop systems encourage the use of bimanual interaction. Navigating and manipulating objects in 3D can be complex in traditional unimanual systems as these actions often have to be mapped from a 2D device to a 3D world. This mapping often requires the user to position the object with two separate movements: firstly in the xy plane; secondly in the z plane. Bimanual interaction systems provide a second device which can increase the degrees of freedom for the system, allowing the positioning of objects in one movement. In the real world people manipulate objects with both hands. As 3D worlds are intended to replicate the real world, users should be able to interact with 3D worlds with both hands.

THRED [50] is a 3D polygonal surface design system that uses two 3D sensors as primary input devices. THRED allows the user to manipulate points and selection areas with the dominant hand and allows context setting and orientation of the view with the non-dominant hand. By using two 3D trackers, users can easily navigate to and manipulate points in a polygonal surface.

The Responsive Workbench [37, 20] is a high resolution tabletop display system projecting a 3D environment that uses bimanual interaction. The user interacts with this environment via a stylus and two pinch gloves. Examples of the bimanual interaction techniques used are: moving both hands apart to scale an object; left hand positioning the model while the right hand rotates it; positioning and orienting the model. The bimanual techniques used were very successful. Unimanual interaction techniques, such as positioning the model and cutting away part of it, were often used together to create new bimanual techniques not explicitly programmed for.

CavePainting [35] is a fully immersive 3D environment for creating 3D works of art in an eight foot cubic space. Props and gestures were used to create the paintings. The props consist of painting tools (a brush and a bucket), a painting table which holds mode selection devices (such as cups into which the paint brush is dipped to select a stroke type), and a pinch glove which can be used for colour selection or setting the brush size. As well as viewing the final artwork, users are also able to view and interact with a replay of the artwork being created. Expert users would often use the glove to change the colour of a brush stroke while applying the paint to the canvas.

2.1.3 Input Metaphors

Input metaphors are interface tools and widgets that are used to interact with systems. The following tools and widgets are based on real world objects.

The alignment stick [45] is a set of tools for treating 2D drawing as sculpting. A mouse and trackball are used to position, orient and size the tool. These tools mimic the behaviour of aligning, planing, cutting, drilling and carving in various forms.For example, the alignment tool aligns each shape it encounters and the carving tool removes parts of the current shape.

Toolglasses [10, 11] are GUI elements that allow tools to be displayed on a transparent palette that is attached to the non-dominant mouse. The tools can be activated by clicking through the tool onto the desired location of the action. Toolglasses save screen space that would otherwise be used to display menus and palettes. Also, because the toolglass is transparent, it does not obscure any of the current work. When combined with Magic Lenses filters [52], toolglasses become even more useful. Magic Lenses filter or distort information on the canvas. They can enlarge items, only show particular items (such as water systems on a town map), display a subset of the properties of items, or show how a graphical distortion would affect the items. A taxonomy of see-through tools demonstrates the scope of toolglasses [9]. An evaluation of toolglasses suggests appropriate transparency levels (around 50%), icon types (solid icons as opposed to text or line art) and background types (solid shapes rather than wire frame or line art) [27].

3D Toolspaces [44] are areas that can contain objects or commands that float alongside the user's avatar in the virtual world but remain out of sight. These toolspaces can be accessed by glances which are gestures made by the non-dominant hand in the direction of the desired toolspace (either up, down, left or right).

Zeleznik, Forsberg and Strauss [54] present a range of bimanual techniques for interacting in a 3D environment. The techniques use two cursors to manipulate objects and viewpoints. Some of these techniques are: non-dominant hand selects point of rotation, dominant hand rotates object; for navigation the non-dominant hand controls height and tilt and the the dominant hand controls forward, backward, left and right motion. The techniques are interesting but other research suggests that adding a second cursor will not improve performance and may even degrade it [33].

2.2 Input Devices

Specialised input devices promise to further enhance bimanual interaction. It is important to use appropriate devices for the tasks given to each hand as the users perception of the input device and the task affects how well the task is performed [32]. The design of input devices is discussed in two taxonomies: Buxton's [13] taxonomy categorises devices by their physical properties, and Card, Mackinlay and Robertson's [16] taxonomy analyses devices based on their expressiveness . This section presents a selection of devices developed for bimanual interaction in two categories: non-dominant hand devices and two-hand devices. Research into modelling input devices is also discussed. As devices for traditional unimanual systems are designed for the dominant hand, the literature concerning input devices for bimanual interaction focuses more on non-dominant hand devices and devices for both hands.

2.2.1 Non-Dominant Hand Devices

Devices designed to be used in the non-dominant hand tend to play supporting roles to the dominant hand. This can be done by setting context or modes for dominant hand actions [50, 42], executing commands [7, 42], executing a specific action [15] or rough positioning of tools and objects [38].

The PadMouse [7] is a mouse for the non-dominant hand which has an integrated touchpad. The touchpad is used to execute commands by gesturing with the user's index finger. An evaluation of PadMouse demonstrated that users could quickly execute up to 32 commands. Another modified mouse is the TouchMouse [28]. This device is able to sense if the user is holding the mouse, and via touch sensors on the left button and on the palm area, how the user is holding it. For example: when the user grabs the mouse, the mouse cursor appears and a quick animation of a circle collapsing in on the cursor can draw the users focus to it; when the mouse cursor is hovering over an icon or button, balloon help could appear as soon as the user touches the left button. An informal evaluation found that users were quick to learn and use the touch sensing features.

PDAs are becoming more common and are easily connected to PCs. This makes them easily available as an input device for the non-dominant hand [42]. As PDAs have touch sensitive displays, they can display a range of different widgets such as scrollbars, buttons, or rotation devices. This gives PDAs great flexibility as a secondary input device. An evaluation showed that PDAs can effectively display up to twelve buttons, are as effective as other devices for scrolling and that it takes 15% longer to home to both the PDA and the mouse rather than just the mouse.

Toolstone [46] is a multiple degree-of-freedom device that senses 3D orientation (see Figure 2.1). This allows the device to sense which way it is facing, which face is currently pointing up and whether the device is flat on the surface. An informal evaluation exposed five pilot users to the system. All understood the concept and could easily use the device.

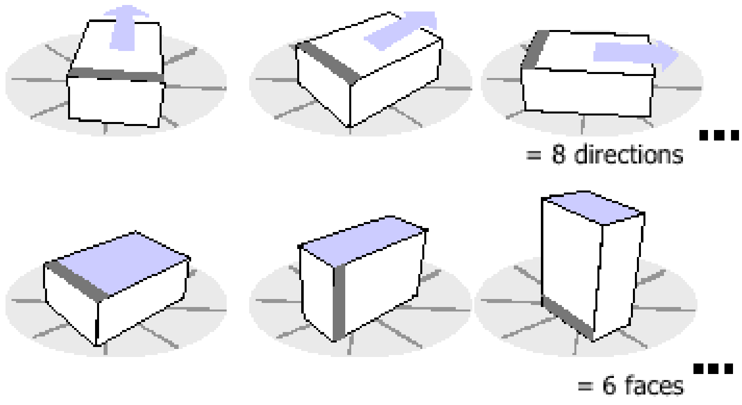


Figure 2.1: The Toolstone can be used to select functions by rotating or flipping it. The different sized faces and orientation tracking provide 48 different functions that can be selected with a single action [46].

2.2.2 Two-Hand Devices

These are devices that are controlled by either both hands together or either hand. Included in this category are devices that have been designed to be used together, such as neurosurigcal props [29].

A set of physical neurosurigcal props [29] allows neurosurgeons to manipulate a 3D model of a head and observe how a cutting plane intersects it. The props consist of a head prop which is a small rubber sphere and a cutting plane which is a rectangular plate. The non-dominant hand orients the head prop and the dominant hand specifies the cutting plane. The user also has access to a trajectory prop to specify a trajectory from the outside of the head to a target in the brain. These props closely map equivalent actions in the real world and the neurosurgeons who have tried it have been very impressed with its ease of use.

The Cubic Mouse [23] allows the manipulation of viewpoints and objects within a 3D world. The device consists of a main cube, three rods, and control buttons. Each of the rods passes through the approximate centre of two faces of the cube, and they are used for manipulating objects in the virtual world. The rods also represent the x, y and z axes of the virtual world. The position of the main cube is bound to the viewpoint of the virtual world, allowing easy manipulation. Typically users hold the device in their non-dominant hand, while the dominant hand controls the rods and buttons.

The ShapeTape [3] is a two-handed device for facilitating the direct manipulation of curves and surfaces. Most techniques for manipulating curves rely on the user understanding and manipulating a mathematical definition of the curve to control its shape. The Shape Tape allows the user to directly create the curve by manipulating a 48 x 1 x 0.1 cm rubber tape. However, more than simply directly manipulating the curve is needed to successfully create curves in 3D space. The addition of a 6DOF tracker to the ShapeTape enables the positioning of the curve in 3D space and an added foot mouse controls the users viewpoint.

2.2.3 Input Device Modeling

Not only is it important to know what devices are available and their function, but it is also necessary to know what devices are possible and how each can interact with systems. Buxton's Three-State Model of graphical input [14] presents a method of modeling the possible states and state transitions for any input device. If it is know what device will be used, then it is possible to model all the actions that can be taken. An input device can be in one of three states: Out of Range, Tracking or Dragging. Some devices can only be in two of the states, for example, a mouse can only be either tracking or dragging as it has no mechanism for sensing if it is being held. This model helps to determine whether a particular device is useful for a particular task. Hinckley, Czerwinski and Sinclair extended this model to handle two input devices and allow states to be annotated with continuous properties such as motion sensing, force used or torque applied [28]. The extension leads to more complicated models and better represents the input states it is possible to achieve in bimanual interaction systems.

Buxton [13] presents a taxonomy of input devices based on their physical attributes as these heavily affect how we interact with them. Card, Mackinlay and Robertson present another taxonomy [16] based on the expressiveness of input devices. Both of these taxonomies are concerned with the physical attributes of input devices and how they affect users and systems.

2.3 Modeling

Understanding how people interact bimanually in both the real world and when using computers is the most important aspect of developing any bimanual interaction system. This section discusses Guiard's Kinematic Chain Theory of asymmetric bimanual action

Guiard's Kinematic Chain Theory [26] is a model of how the human body behaves in asymmetric bimanual action. The model has three main observations:

- Spatial Reference in Motion. The non-dominant hand provides a frame of reference for the dominant hand.
- Scale of motion. The dominant and non-dominant hands work on different scales of motion. The dominant hand moves in small increments quickly, while the non-dominant hand moves in larger increments slowly.
- Precedence of action. Usually the non-dominant hand precedes the dominant hand in motion.

Guiard's theory applies to asymmetric bimanual actions in everyday life. These observations also apply to asymmetric bimanual interaction with computers. It is important to note that bimanual interaction will be effective only if due consideration is given to the tasks assigned to each hand. It is possible for two-handed systems to be slower than the unimanual equivalents if completely independent subtasks are assigned to each hand. However, if a system is consistent with Guiard's observations then the interaction should feel more natural [33]. Evaluations based on Guiard's observations have demonstrated how the importance of the roles each hand plays increases as the task difficulty increases [31], and how well designed bimanual interaction requires less visual attention/feedback than the equivalent unimanual interaction [30]. However if visual feedback is not present then better performance is produced if the input devices have the same origin [4].

2.4 Evaluations

This section discusses evaluations of bimanual interaction techniques and theories.

Buxton and Myers [15] compared the use of a dedicated scrolling device for the non-dominant hand and a mouse for selection to the use of a mouse for scrolling and selection as in normal applications. They found that expert users were 15% faster in the two-handed condition than in the one-handed and novices were 25% faster in the two-handed condition. This gain for bimanual interaction was supported by Gribnau and Hennessey [24] who compared bimanual and unimanual techniques for 3D object assembly. They found bimanual interaction to be 17.5% faster than unimanual interaction.

Dillon, Edey and Tombaugh [21] studied the cost of command selections. They compared five command selection methods: a one-mouse (traditional) method, a voice method, and three bimanual methods: one touchscreen, and two two-mice (two pointers) methods, one with larger command buttons. All command selections were made with the non-dominant hand except in the voice condition. The results showed that the voice and touchscreen methods were significantly faster than the other three.

Kabbash, Buxton and Sellen [33] compared four techniques for a compound drawing/colouring task: a unimanual technique, a two-pointer technique, a technique in which the non-dominant hand controls the position of a floating palette, and a toolglass technique. The results showed that the toolglass technique was the fastest while the other three had no significant difference among them, though the two pointer technique was slightly slower than the one handed technique. The most important observation gained from this experiment is that simply adding another input device does not necessarily result in performance gains.

MacKenzie, Sellen and Buxton [41] compared the effectiveness of three input devices (mouse, trackball and tablet with stylus) in elemental pointing and dragging tasks. The tablet was the most effective, followed by the mouse and then the trackball. Kabbash, MacKenzie and Buxton [34] conducted a similar experiment comparing the effectiveness of these input devices across both hands. They found that the dominant hand was faster with all the devices, but the non-dominant hand was more accurate with the trackball, though this was still the slowest device for both hands. They also found that the tablet was the fastest, then the mouse and then the trackball.

Balakrishnan and Kurtenbach [6] studied bimanual camera control and object manipulation in 3D environments. For a target selection task, they found the bimanual technique to be 20% faster than the unimanual technique. However, for the more complicated docking task, the bimanual technique was only significantly faster for the last set of tasks.

Leganchuk, Zhai and Buxton [39] studied whether bimanual interaction provided cognitive as well as motor benefits. The problem studied was selecting minimal bounding boxes around geometric shapes. The initial experiment showed that the bimanual techniques used were significantly faster than the unimanual technique. The times to re-acquire control points to resize the bounding box were removed. These times represent most of the motor benefits of the bimanual techniques. The new times had no significant difference between them, though there was a significant interaction between technique and size. This interaction showed that the bimanual techniques were better at the harder, larger tasks, and worse at the easier, smaller tasks. These results strongly indicate that there is cognitive as well as motor benefits to bimanual interaction. The initial experiment was repeated in Chapter 5.

Balakrishnan and Kurtenbach [5] investigated symmetric bimanual interaction and how attention, speed and visual integration of the tasks affects performance. The task was to keep the left and right hand cursors above their respective targets. The distance between the targets, the speed at which they moved and whether or not they were visually connected were altered between tasks. As the task difficulty increased (greater distance between targets, not connected and faster moving) the participants adopted a sequential style, first moving one cursor and then the other. The findings suggest that symmetric bimanual tasks should keep both targets close together and visually connected.

Chapter III

Design Principles for Bimanual Interaction

This chapter introduces a set of four principles to assist in the design of bimanual interaction systems. Principle One discusses the importance of understanding how people's hands work together. Principle Two emphasises the use of appropriate actions and devices for input. Principle Three encourages eliminating modes. Principle Four discusses the use of bimanual techniques to maximise screen space and minimise time to target and attention switching. The following principles encapsulate and distill current understanding of bimanual interaction.

This thesis uses the terms dominant hand and preferred device. For a right handed person, the dominant hand is the right hand and the preferred device is the device assigned to the dominant hand. This distinction has been made because some participants in the experiments in Chapter 5 were left handed, but used a mouse with their right hand.

3.1 *Principle One: Assign Appropriate Roles to the Appropriate Hand*

When assigning roles to hands, the designer must consider: what the task is; how it would be accomplished without the use of a computer; and what advantages a computer can supply for that task. The designer also needs to understand how people use their hands. Guiard's Kinematic Chain Theory, a model of asymmetric bimanual action, aids understanding how we use our hands [26] (See Section 2.3). The theory reveals that the non-dominant hand is better suited to performing tasks that support the dominant hand. Examples of such tasks are: rough positioning/placing of objects; controlling views; and context setting. The dominant hand is better suited for precise actions such as: positioning/placing; selecting objects; and fast, accurate movements. Exactly which roles each hand will take depends upon the task for which the system is being designed.

Designing for bimanual interaction involves more than providing the user with two input devices. The system must be designed to take advantage of the ways in which people use their hands. In traditional unimanual systems the dominant hand does most of the work and the non-dominant hand activates modifier keys or command shortcuts. However, in everyday life the non-dominant hand has a more active role. When writing or drawing by hand, the non-dominant hand steadies and moves the page to provide better control over the work. It is these types of tasks that the non-dominant hand is unable to do in traditional unimanual systems, but is assigned to in a bimanual system.

3.2 Principle Two: Use Appropriate Actions and Devices for Input

To develop easy to use bimanual systems, the designer needs to consider what tasks the system will do and understand how each of those tasks is done in the real world. For example, consider drawing a straight line between two points. Two tools are needed: a pencil and a ruler. The ruler must be positioned correctly and then held steady while the line is drawn. If the line is long enough, both hands need to be used to position the ruler. Mapping these actions to interactions could be done in two ways: each hand positions an end point of the line; or the dominant hand selects an end point and sweeps the line out to the other end point. The former mimics the action of positioning the ruler (ruler method) and the later mimics the drawing of the line (line method). While the line method may seem to be the most appropriate mapping, it requires the user to commit to the location of one end point before any feedback is available. The ruler method, however, allows the user to fully position the line before committing to the location of either end point.

Once the tasks have been considered and appropriate actions decided upon, the designer needs to contemplate which devices are appropriate to use. The way the user perceives a device to work affects how well that device will be used [32]. The input devices need to reflect the tasks and the roles that they will play. For example, the dominant hand is good at precise selection tasks and, if appropriate, should be given an input device that affords precise selection such as a stylus, or a scalpel-like device.

3.3 Principle Three: Exploit Bimanual Capabilities to Eliminate Modes

Modes are different states of a system in which the same action can mean different things. Modes should be used with caution as they tend to restrict the availability of actions and their effects, and increase the users memory load as they must be aware of which mode they are in and how to switch between modes [1].

Bimanual interaction systems provide means to eliminate modes. For example, to draw shapes in a traditional unimanual drawing system, the user must select the desired shape mode, then the location to draw the shape. In a bimanual drawing system that uses toolglasses, the user selects the shape and the location at the same time, removing the need for any shape modes and relieving the user of the need to remember what the current shape mode is. The two input devices allows actions that in traditional unimanual systems are serial actions, such as positioning and scaling an object, to be done in parallel. Tasks like positioning and scaling a circle to fit inside a box are substantially easier when controlling both properties simultaneously [38]. The extra degrees of freedom in a bimanual system allow the elimination of movement modes in 3D systems. In traditional unimanual 3D desktop systems, navigation often requires two separate actions: navigation in the xy plane and navigation in the z plane. Bimanual systems allow these navigation modes to be merged so that movement is one combined action of both hands.

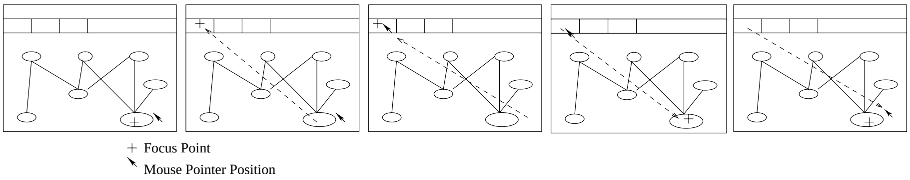


Figure 3.1: The attention switching process. For the user to activate a menu command, the menu item must be found, the mouse moved to the item, the item activated, the original position then relocated and the mouse returned there.

3.4 *Principle Four: Exploit Bimanual Capabilities to Increase Usable Screen Space, Reduce Attention Switching and Reduce Time To Target*

High powered systems have hundreds of commands available to the user, and each command or group of commands that have a button, or toolbar, or menu, uses screen space that could be available for displaying the workspace. Bimanual interaction techniques can be used to increase the usable screen space. For example, toolglasses [10, 11] allow menu items and command buttons to be placed on the toolglass, removing the need for fixed toolbars and increasing the amount of screen space available for the workspace. When there are hundreds of commands it is not practical to display them all on one toolglass. The use of a device such as the toolstone [46] (see Section 2.2.1) with a different toolglass bound to each orientation gives the user quick access to 48 different toolglasses. If each toolglass can hold eight or ten tools, then 384 to 480 tools are easily available. None of these tools use any significant screen space as each of them is displayed on a transparent movable toolbar.

Attention switching is when the user's focus shifts from the current object to another object. When a user is forced to switch his/her attention from the current object to select a tool or command from the toolbar and then back, their line of thought can be interrupted (see Figure 3.1). Bimanual interaction systems can reduce the amount of attention switching. For example, the toolglass input metaphor requires the tool to be applied directly to the object, keeping the user's focus on the object rather than the tool.

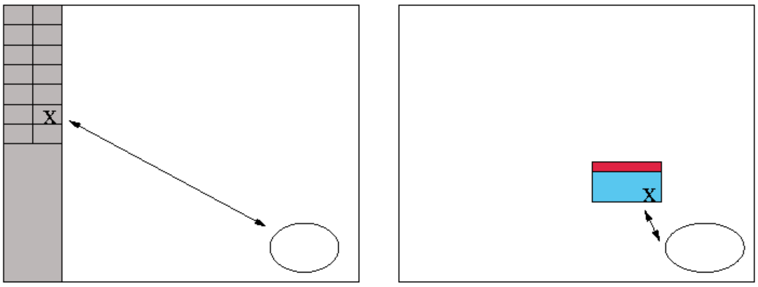


Figure 3.2: Reducing time to target. By having the menu closer to the object the time taken to get between the menu and the object is reduced.

The time taken to move the mouse from its current position to the desired location is described by Fitts' law [22]. Fitts' law states that the bigger and closer a target is, the quicker it can be acquired. This means that the most often used tools should be either the closest tools to the pointer or have the largest icons. If large icons are used, then the usable screen space is reduced. The problem then becomes how to keep the tools near the pointer. Using techniques such as toolglasses allows the tools to be positioned by the non-preferred device. As the non-dominant hand provides the dominant hand with a frame of reference [26], the tools will always be near the pointer, reducing the time to target (see Figure 3.2).

Chapter IV

Developed Systems

This chapter discusses the design and implementation of two bimanual systems and their unimanual equivalents. The first is a variant of the Data Mountain [47]. The second is a vector based drawing tool. Both systems are written in Tcl/Tk [51] and the bimanual versions use the Tcl groupware extension Groupkit [48] to allow a mouse on a second computer to act as if it were connected to the main computer. Due to limited resources, both systems use two mice rather than Specialised input devices.

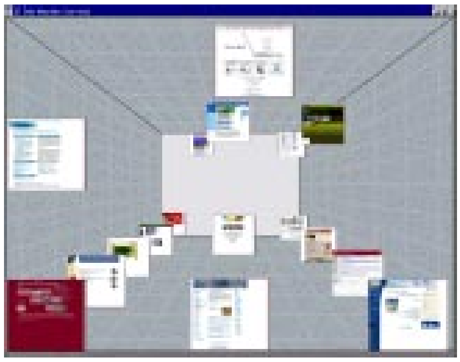
4.1 Data Mountain Based Systems

The Data Mountain [47] was designed to allow rapid retrieval of thumbnails representing web pages by taking advantage of spatial cognition. Users were able to place documents at arbitrary positions on an inclined plane in a 3D desktop virtual environment (see Figure 4.1(a)). This interface did not allow the user to "float" the thumbnails above the plane. The Data Mountain was modified to investigate the effectiveness of spatial memory in 2D and 3D physical and virtual environments [19]. The modified version used a "well" style 3D interface. The user appears to be looking down a well and is able to position thumbnails anywhere within the confines of the well, with the thumbnails closer to the bottom being smaller than those nearer to the top (see Figure 4.1(b)). The modified version was adapted to allow bimanual interaction.

4.1.1 Unimanual Data Mountain Uni-DM

In the unimanual Data Mountain [19], one mouse is used to control the x,y and z coordinates of the thumbnails. The user selects a thumbnail with the left mouse button and is able to move that thumbnail up, down, left and right

(a) The original Data Mountain interface [47]



(b) The modified Data Mountain interface [19]

Figure 4.1: The original and modified Data Mountains

(xy plane, parallel to the screen). To move a thumbnail down into the well or up out of the well, the user selects the thumbnail with the middle mouse button, pulling the mouse back towards him/herself to pull the thumbnail out of the well and pushing the mouse forward to sink the thumbnail back down the well. The third mouse button allows the user to view a large version of the thumbnail, including its title.

4.1.2 Bimanual Data Mountain Bi-DM

The bimanual Data Mountain (implemented for this thesis research) uses two mice for the interaction. The preferred mouse is used to select a thumbnail and move it in the xy plane. While the thumbnail remains selected, moving the non-preferred mouse forward or backward moves the thumbnail deeper or shallower. As in the unimanual version, the right button on the preferred mouse enlarges the thumbnail and displays the title. The following sections discuss how the principles were used to develop this system.

Principle One: Assign Appropriate Roles to the Appropriate Hand

The bimanual Data Mountain has two main interactions: the selection of a thumbnail and the movement of the thumbnail. The selection task requires precise and quick movements with the focus of the user on the pointer as well as the target. Principle One states that this type of task should be given to the dominant hand.

Principle Two: Use Appropriate Actions and Devices for Input

Principle Two states that appropriate actions and devices should be used for input. The preferred mouse selects the thumbnails so its pointer must be visible. Assigning the x and y movement of the thumbnail to the preferred mouse means that the thumbnail will follow the visible cursor, and not produce conflicting visual feedback. The non-preferred mouse actions were chosen to mimic an object being pushed away from and pulled closer to the user.

Principle Three: Exploit Bimanual Capabilities to Eliminate Modes

The presence of two mice enables actions to be performed in parallel. By assigning the xy movement to the preferred mouse and the z movement to the non-preferred mouse, the positioning of the thumbnails can be performed in one combined movement, eliminating the two movement modes.

4.2 Drawing System

Uni-Draw and Bi-Draw (both implemented for this thesis research) are vector based drawing programs designed to have identical functionality. Figures 4.2 and 4.3 show the respective interfaces. The majority of each interface is used by the canvas. The rest is used by the toolbar (Uni-Draw) or the toolglass. (Bi-Draw).

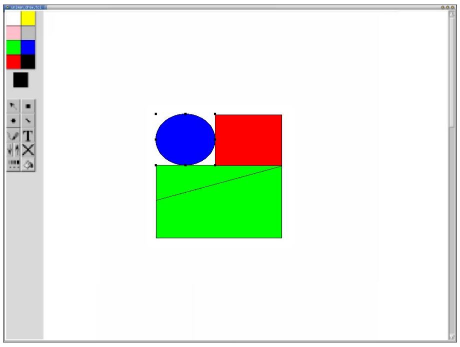
The toolbar and the toolglass have the same functionality. Each holds an identical set of tools for drawing on the canvas. The tool set contains three subsets of tools: colour tools, object creation tools and line editing tools. The colour tools are display constantly and the object creation tools and line editing tools can be switched between. The line editing tools enable the user to change the thickness and colour of the outlines of existing ovals and rectangles and the colour and thickness of existing lines. The object creation tools are describe below.

- Selection: This command allows the user to select, move and resize most objects on the canvas. Text is not able to be resized.
- Fill: Allows the user to change the colour of existing objects.
- Create Object (Rectangle, Oval, Line): Creates the desired object at the specified location.
- Free Hand Draw: Allows the user to draw as though a pencil is being used.
- Create Text: Creates a cursor at the selected point, allowing the user to type text. The cursor is removed once the enter key is pressed or the mouse button is clicked elsewhere.
- Raise/Lower: Allows the user to raise or lower an object to be either at the lowest level of objects, so it lies under every other object, or to the highest level, so it lies over every other object.
- Delete: Allows the user to remove items from the canvas.

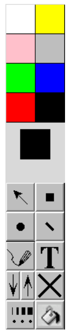
4.2.1 Uni-Draw

The unimanual version of the drawing system is quite similar to many other basic drawing programs. The interface consists of two sections: the toolbar and the canvas. The toolbar is on the left of the canvas and has dimensions of 100x974 pixels, with the command buttons and the colour buttons having dimensions of 40x40 pixels. The canvas has dimensions of 1145x974 pixels, giving the total size of the interface as 1245x974 pixels (see Figure 4.2(a)).

Interaction with the system only uses the left mouse button. The user can select the colour or mode by clicking on the desired colour or button on



(a) Uni-Draw interface. The blue circle is currently selected and has eight handles which can be used to resize it.

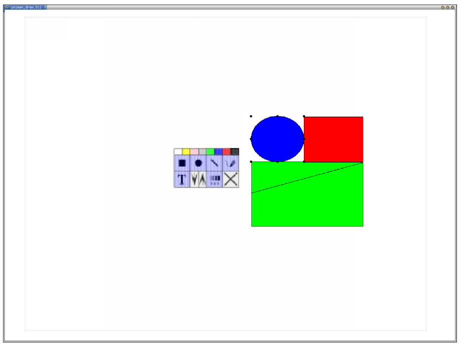


(b) Uni-Draw toolbar

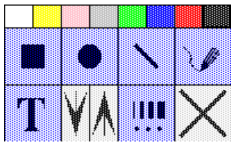
Figure 4.2: The Uni-Draw interface and enlarged view of the toolbar.

the toolbar. The current colour is shown in the colour indicator box between the colour bar and the create/edit bar (see Figure 4.2(b)). When a command button is pressed, it remains in the pressed position, indicating that it is the current mode, until another button is pressed.

To create a rectangle, oval or line, select the appropriate mode, click and hold the left button with the mouse cursor above the desired location for one corner of the object and then drag out the object to the desired size. Text creation requires the user to select the text mode, click on the point where the text is desired and then start typing. Freehand draw mode creates a small circle beneath the cursor each time the cursor is moved when the left mouse button is pressed. The selection mode allows the user to select items by clicking on them or to select the topmost item in a group by clicking and dragging over the group. Once selected, an item can be moved by grabbing anywhere in the interior of the object, or resized by grabbing one of the handles bordering the object (see Figure 4.2(a). The other tools: raise/lower, delete, fill, and the outline edit tools, all activate when the user clicks on an object in the canvas.



(a) Bi-Draw interface. The user's non-dominant hand controls the position of the toolglass.



(b) Bi-Draw toolglass

Figure 4.3: The Bi-Draw interface and enlarged toolglass

4.2.2 Bi-Draw

The interface is shown in Figure 4.3(a). The entire interface is taken up by the canvas as the toolbar is now located on a toolglass that is bound to the non-preferred mouse. This means that the canvas size is 1245x974 pixels, 97400 pixels bigger than in Uni-Draw. The toolglass is 200x120 pixels, the buttons are 50x50 pixels, the colour bar sits directly above the create/edit bar and the colour buttons are 25x20 pixels (See Figure 4.3(b)). The following sections discuss how the principles were used to develop this system.

Principle One: Assign Appropriate Roles to the Appropriate Hand

Movement of the toolglass is bound to the non-preferred mouse to ensure that the non-dominant hand is in a supporting role to the dominant hand. The user is always in the selection mode, allowing the selection, movement and resizing of objects in the canvas with the preferred mouse. Interactions are in accordance with Guiard's Kinematic Chain theory, which is the basis for Principle One. To draw an object onto the canvas, the user needs to: position the toolglass in the approximate location of the desired object/action (non-dominant hand precedence of action); click and hold through the toolglass

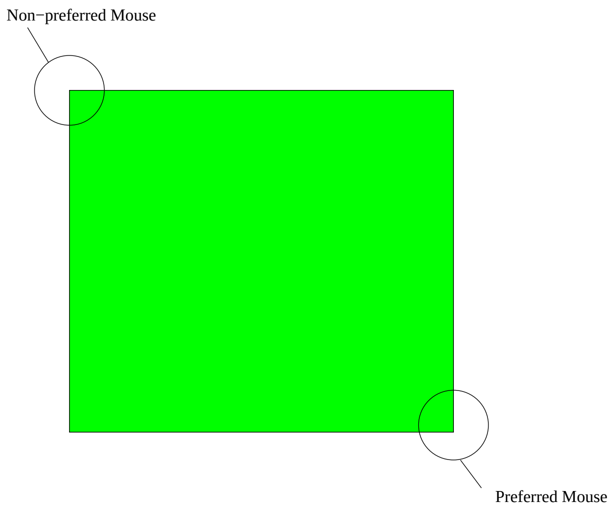


Figure 4.4: Drawing a rectangle in the Bimanual System. The non-preferred mouse controls one corner, in this case the upper left corner, and the preferred mouse controls the opposite corner, in this case the bottom right corner.

onto the canvas/object (Spatial Reference); the toolglass disappears and the non-preferred mouse is able to control the position of one corner of the object and the preferred mouse the opposite corner (see Figure 4.4) (symmetric action, Guiard theory does not hold); release the left preferred mouse button once the object is positioned and the toolglass reappears.

Principle Two: Use Appropriate Actions and Devices for Input

The use of both mice to position and size the objects mimic how people position large objects in every day life. Text creation is similar, but instead of a click and hold to select the tool, a click and release is used and the user is able to type. The user exits the text mode by either pressing enter or pressing the left button on the preferred mouse. The fill command is activated by positioning the desired colour over the item and then clicking through the colour onto the item. This also sets the current colour so the next object drawn will be that colour. The current colour is indicated by a heavy black border surrounding it. The other commands (raise/lower, delete and the edit line tools) all work by clicking through the tool onto the target.

Principle Three: Exploit Bimanual Capabilities to Eliminate Modes

The tools on the toolglass are applied directly to the objects or the canvas, removing the need for persistent tool modes and reducing the memory load of the user.

When objects are created, the preferred and non-preferred mice control the positions of opposite corners of the object (see Figure 4.4). This allows the objects to be positioned and scaled at the same time, eliminating the need for the separate move and scale modes that Uni-Draw has.

Principle Four: Exploit Bimanual Capabilities to Increase Usable Screen Space, Reduce Attention Switching and Reduce Time To Target

The use of a toolglass bound to the position of the non-preferred mouse allows an increase in usable screen space by 97,400 pixels within a window of identical size. It also allows the reduction of time to target and the amount of attention switching as the user can activate any command by positioning the desired command over the desired location.

Chapter V

Experiments and Results

This chapter presents three experiments investigating bimanual interaction. The first studies bimanual interaction in a simple 3D environment, as described in Section 4.1. The second studies a basic drawing system, as described in Section 4.2. The third repeats an earlier experiment and investigates explanations for the unexpected results of the first two experiments. A brief description of each system is followed by the experimental design, results and statistical analysis and finally the discussion of the results.

5.1 Experiment 1: 3D Data Mountain

This experiment compared bimanual and unimanual interaction in a "well" style 3D environment (see Figure 5.1 using a modified version of the Data Mountain [19] (see Section 4.1). The Data Mountain allows a user to place documents in a 3D space to take advantage of their ability to use spatial memory to store and retrieve documents. Bimanual and unimanual versions (Bi-DM and Uni-DM) of the modified Data Mountain were compared.

Bi-DM is expected to be faster as it allows the thumbnails to be positioned in the xy plane and the z plane at the same time (Principle Three). This parallelism is not possible in Uni-DM.

5.1.1 Experimental Design

The primary purpose of the experiment was to determine whether bimanual and unimanual interaction techniques differ in efficiency. Eighteen first year computer science students participated. Their subjective assessments of the interaction techniques were recorded as well as the times taken to complete each task. The times were recorded using a stopwatch. Participants were asked to complete two tasks with each interface, one practise task and one

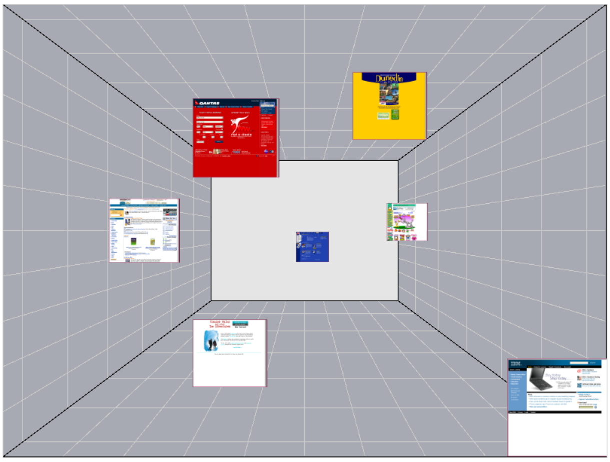
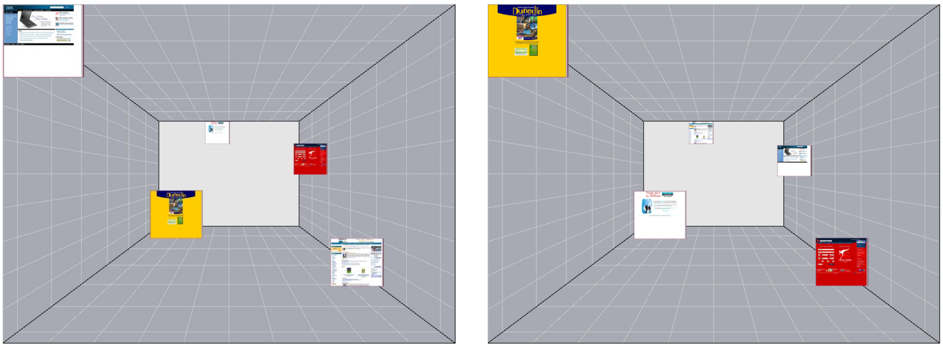


Figure 5.1: Data Mountain Interface

timed task. Each task required the participant to approximately duplicate an arrangement of thumbnails of web pages shown to them on an A4 printout. The pages were chosen for their distinctive appearance and recognisable names. The participant was allowed to study each arrangement for fifteen seconds, then was required to complete the tasks. They were told that speed was more important than accuracy. The participants were able to refer to the paper printout of the arrangement during the task. The practise task had five thumbnails and the timed task had seven thumbnails for both Bi-DM and Uni-DM. The order of the interfaces was counterbalanced across each participant.

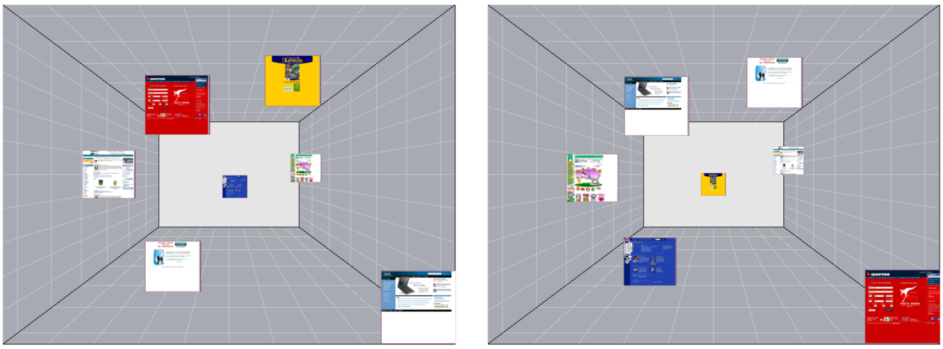
There were four different arrangements of the thumbnails, two with five thumbnails and two with seven. Figure 5.2 shows the practise tasks which are similar in layout except that the positions of the thumbnails have been exchanged. Tasks 1 and 2 (Figure 5.3) also have similar layouts, with the position of the thumbnails exchanged. The layouts between the tasks were similar to ensure that each interface had tasks of similar difficultly, and the thumbnails exchanged position to counter learning between the tasks. After completing each task, the participants were asked to respond to the question "This interface is efficient for the task" (1 being disagree and 5 being agree). Finally each participant was asked to indicate which version they preferred.



(a) Practise task 1

(b) Practise task 2

Figure 5.2: Data Mountain practise tasks



(a) Timed task 1

(b) Timed task 2

Figure 5.3: Data Mountain timed tasks

	The interface was efficient for the task	Ranking
Bi-DM	4.4 (s.d. 0.85)	1.4
Uni-DM	3.9 (s.d. 0.998)	1.6

Table 5.1: Mean Likert Responses and Ranking of the modified Data Mountain

5.1.2 Results

All the participants enjoyed taking part in this experiment and most indicated that the bimanual version was easier to use. None of the eighteen participants had encountered any versions of the Data Mountain previously.

Bi-DM was slightly faster than Uni-DM. The mean times for completing each task in Bi-DM and Uni-DM were 32.05 (s.d. 10.81) and 35.51 (s.d. 11.64) seconds respectively. This is just outside the 95% confidence interval ($t(16)=5.46$, $p=0.053$). The slightly faster times for Bi-DM (as expected) were because of the efficiencies of bimanual interaction over traditional unimanual interaction. For the modified Data Mountain systems, bimanual interaction techniques eliminated the xy plane/z plane movement mode, allowing the participants to place thumbnails with one combined movement rather than two separate actions. Although the difference between the mean task times lies just outside the 95% confidence level, the results indicate that there may be time advantages for bimanual interaction when serial input modes are combined into parallel input.

Over half of the participants (11 out of 18) commented that the bimanual system was easier to use once they became accustomed to it. They also found that Bi-DM took longer to learn than Uni-DM.

The participants preferred Bi-DM, though not significantly so. Table 5.1 shows the means for the subjective assessment of Bi-DM and Uni-DM. There is no significant difference for the 5-point Likert scale questions (Mann-Whitney U Test, $U=178.5$, $N=18$, $p=0.11$) nor is there a significant difference for ranking of preference (Mann-Whitney U Test, $U=198$, $N=18$, $p=0.11$).

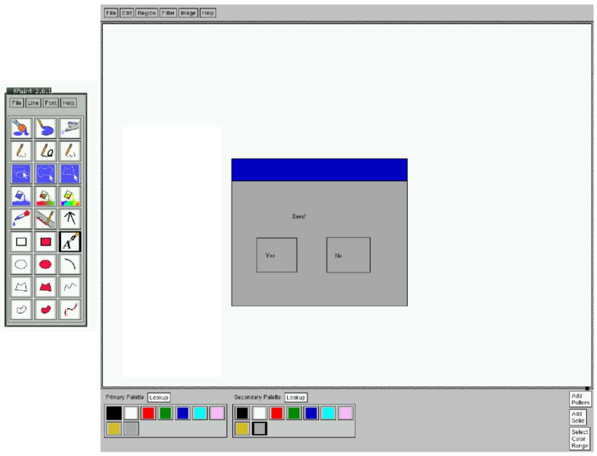


Figure 5.4: Xpaint menu and interface

5.1.3 Discussion

Most regular computer users already have a reasonable skill level in controlling the mouse with their dominant hand. This means that any new unimanual system presented to these users could be easier to learn than an equivalent bimanual system. Despite this the slightly faster times of Bi-DM suggest that learning to use a bimanual system takes no longer than learning to use an equivalent unimanual system. None of the participants were familiar with the modified Data Mountain before taking part in the evaluation. This indicates that the only advantages in either system were based on the type of interaction, rather than on familiarity.

5.2 Experiment 2: Drawing Systems

Three drawing systems were compared: a bimanual interaction system (Bi-Draw) described in Section 4.2.2, and two unimanual interaction systems (Uni-Draw, described in Section 4.2.1, and Xpaint). Xpaint is a standard paint program available on most Unix/Linux machines (see Figure 5.4). Xpaint was used to train the participants, allowing them exposure to the tasks to reduce the amount of learning between Bi-Draw and Uni-Draw.

5.2.1 Experimental Design

The primary purpose was to determine which drawing technique was the most efficient. The participant's subjective assessments of the various interfaces/interaction techniques were also recorded.

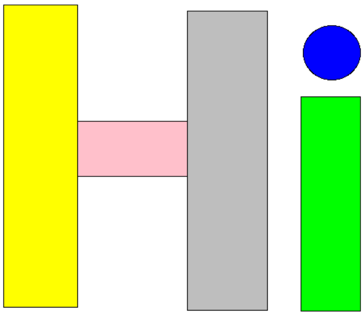
The experiment was a one-factor, within-subjects, analysis of variance (ANOVA) of the independent variable 'interface' (Xpaint, Bi-Draw, Uni-Draw). Each participant completed three tasks with each interface. Always starting with Xpaint, the order of the bimanual and unimanual interfaces were then exchanged for each consecutive participant. Each participant was given two minutes to familiarise themselves with the relevant parts of the interface before attempting any of the tasks. The tasks are shown in Figure 5.5. For each task, the participant was shown the desired image on A4 paper and was given fifteen seconds to study it. Then the participant was instructed to draw the image on the current interface as quickly as possible. They were told that speed was more important than accuracy. Task 1 (Figure 5.5(a)) was a training task aimed at familiarising subjects with the interfaces. Tasks 2 (Figure 5.5(b)) and 3 (Figure 5.5(c)) were timed tasks. On completion of each task, the participant was asked to respond to the statement "This interface is efficient for the task" on a five point Likert scale (1 being disagree and 5 being agree). After the 3 tasks were completed with all three interfaces, the participants were asked to rank the interfaces in order of preference, 1 being the most preferred and 3 being the least preferred.

5.2.2 Results

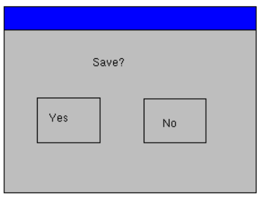
Eighteen subjects, all first year computer science students, participated in the experiment. Uni-Draw had the lowest task completion times, followed by Xpaint and then Bi-Draw. The mean times for completing each task in Xpaint, Bi-Draw and Uni-Draw were 33.08 (s.d. 9.04), 49.46 (s.d. 13.63) and 25.85 (s.d. 6.34) seconds respectively (see Figure 5.6). This is a significant difference ($F(2,34)=84.229$, $p=0.000$). Calculating the Scheffé Confidence Interval returns an SCI of 4.77, showing that there is a significant difference between each of the interfaces.

The participant's comments suggested strong reasons for the much slower

(a) Practise Task



(b) Task 1



(c) Task 2

Figure 5.5: Tasks for drawing systems experiment

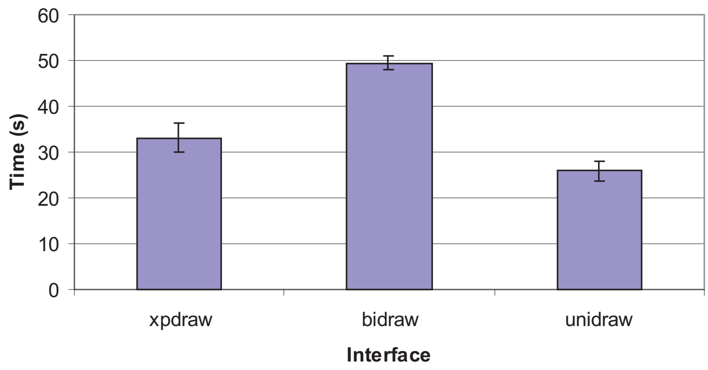


Figure 5.6: Draw mean task completion time. Error bars show one standard error above and below the mean.

	Xpaint	Bi-Draw	Uni-Draw	Significant Difference
Task 1	3.61 (s.d.0.92)	3.81 (s.d. 0.94)	4.31 (s.d. 0.65)	✗
Task 2	3.53 (s.d.0.88)	3.75 (s.d. 0.94)	4.28 (s.d. 0.64)	✔

Table 5.2: Mean Likert Responses

time of Bi-Draw. Most participants (14 out of 18) commented that Bi-Draw would be much better once they became accustomed to using it. Many of the participants also commented that their lack of familiarity with Bi-Draw led to them ranking it below Uni-Draw. One participant, after using Xpaint and then Bi-Draw, commented on the sophistication of Bi-Draw, saying that it was “kind of like painting with paints instead of drawing with crayons”.

Each participant was asked to rate the efficiency of each interface after each task on a five point Likert scale (see Figure 5.2). Uni-Draw was the most preferred system. There was no significant difference in the ratings of the interfaces on Task 1 (Friedman Test, χ_r^2=5.03, df=2, N=18, p=0.081). However, Task 2 showed a significant difference (Friedman Test, χ_r^2=6.86, df=2, N=18, p=0.032). The average rankings were: Xpaint 2.5, Bi-Draw 2, Uni-Draw 1.5.

5.2.3 Discussion

This experiment suggests that, contrary to prior work, bimanual systems are less efficient that unimanual systems. This contradicts findings from the first experiment and prior research. Four possible explanations are:

- H1 — Quality of the non-preferred mouse. During trial runs of the experiment, it was noticed that the non-preferred mouse was less sensitive than the preferred mouse. This difference in quality was not thought to be significant. Given the unexpected results, this is one explanation that needs to be considered. Research indicates that lag of about 255ms can degrade the performance of a system by approximately 64% for tasks with a Fitt's law index of difficulty of approximately 1.5 [40]. Therefore, even for relatively simple tasks, lag can have a large effect on the time taken to complete a task. However, if the mean task completion time of Bi-Draw is decreased by a factor of 1.64 ($49.46/1.64 = 30.16$ — a 64% increase on 30 seconds is 49 seconds) then the time becomes more comparable with Uni-Draw.

- H2 — The amount of accuracy required to complete the tasks. All previous experiments have required a high level of accuracy whereas our experiments focused on speed, with the participants only completing the task approximately.

- H3 — The amount of training provided. Many participants felt that they would improve with Bi-Draw as they used it longer. Given that the participants were unfamiliar with bimanual interfaces and that most had previously used unimanual drawing tools, the amount of training the participants had might not have been sufficient. Unfortunately there is very little information on how much training is sufficient for a fair comparison. A quick review by the author on the training techniques of twenty two prior papers revealed huge variations in the amount and type of training provided. It is apparent that research into the amount of training necessary for a fair comparison between bimanual and unimanual systems is needed

	Bi-Draw	Uni-Draw	Is Bimanual Faster?
Expert Task 1	13.55	14.65	✔
Expert Task 2	11.84	14.14	✔
Expert Task 3	12.5	12.1	✗
Expert Task 4	10.44	11.85	✔
Average	12.08	13.19	✔

Table 5.3: Task times for expert evaluation

- H4 — The implementation of the system. While being very similar in function and design, Bi-Draw and Uni-Draw differed in implementation. For example, the colour bar for Uni-Draw had buttons that were approximately twice the size of the colour bar buttons on Bi-Draw; and as the toolbar remained in one location in Uni-Draw, the participants spent less time locating it.

5.2.4 Expert Evaluation

The participants were unfamiliar with Bi-Draw and had only a short time to practise with it before completing the tasks. To estimate the maximal performance and to investigate H2, an experiment involving an expert user (the author) was conducted. The expert user trained for approximately three weeks by using the mouse with his non-dominant hand for day to day computing, and in the last week, spent several hours with both Bi-Draw and Uni-Draw. The expert user was timed in completing four drawing tasks with both Bi-Draw and Uni-Draw. The average times were 12.08 seconds and 13.19 seconds respectively (see Table 5.3).

The expert evaluation of Bi-Draw showed that even with extensive practise there is little difference between the two interfaces. To achieve this level of competency with Bi-Draw required a training period of approximately three weeks. This suggests that bimanual interaction provides few advantages over traditional unimanual interaction, which is contrary to prior work. The possible explanations for the poor performance of the expert user with Bi-Draw include: the quality of the non-preferred mouse (H1); the accuracy requirement of the tasks (H2); and the implementation of the system (H4).

5.3 Experiment 3: Minimal Bounding Box

The results from the previous two experiments are contrary to prior research findings. While the difference in the mean task times for the first experiment lie just outside the 95% confidence level, the results from the second experiment strongly show that bimanual interaction is slower than traditional unimanual systems. While training does improve the performance of the user, the hypotheses we wish to explore concern the quality of the non-preferred mouse (H1) and the accuracy requirement of the tasks (H2). It is felt that the combination of one of these hypotheses and the lack of training (H3) is the main cause of the poor performance the bimanual systems.

To test these hypotheses an experiment based on the minimal bounding box experiment [39] was run. If the results from our experiment agreed with the results from the original, then H2 would be the most likely explanation. Otherwise H1 would be the strongest explanation. The minimal bounding box experiment was chosen as it had a high accuracy component,a specific application domain, and was well documented. Figure 5.7 illustrates the minimal bounding box problem.

5.3.1 Experimental Design

The times taken to sweep out a minimal bounding selection area on basic geometric shapes were compared.

Three techniques were used: a traditional unimanual version with a floating palette (unimanual), a bimanual version with a floating palette (bimanual stretchy) and a bimanual version with a toolglass (bimanual toolglass).

The floating palette in the unimanual and bimanual stretchy techniques could be moved with the preferred mouse by clicking and dragging on the top border, while the toolglass in the bimanual toolglass technique was controlled by the non-preferred mouse.

The palette and toolglass both contained two tools, the rectangle selection area and the oval selection area. The tool palette behaved similarly to

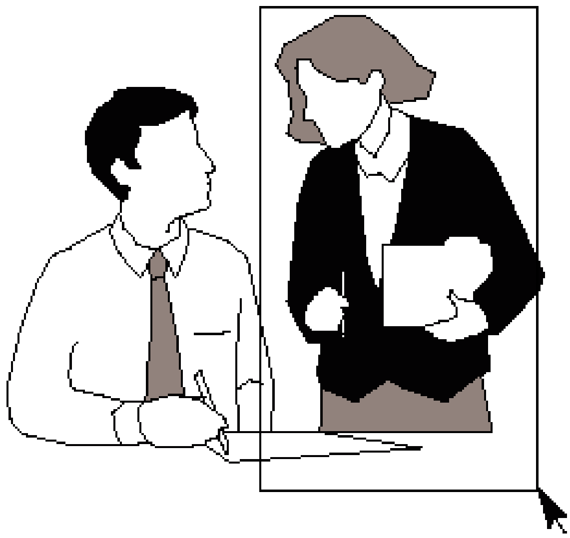


Figure 5.7: Generalised example of the bounding box issue. The user is currently dragging out a selection box. The initial mouse press at the top left was incorrect as they are including part of the man's arm unintentionally [39].

traditional tool palettes and the toolglass behaved in the same way as the toolglass for Bi-Draw.

Two geometric shapes (rectangles and ellipses) were used for the tasks. To select an ellipse, a rectangular selection area was used and the participant was required to line up the selection area so that it touched (within one pixel) the top-most, left-most, right-most and bottom-most points of the ellipse. To select a rectangle, an elliptical selection area was used and the participant was required to line up the ellipse so that it touched all four corners of the rectangle (see Figure 5.8). Correctly selecting the rectangular shapes is more difficult as there is not a strong visual connection between the control points and the selection area. For both of the bimanual versions, each mouse controlled opposite corners of the selection area.

The tasks were timed from when the participant selected the correct tool and finished when the task was completed. A complete task has four red dots at the points where the selection area touches the shape, within one

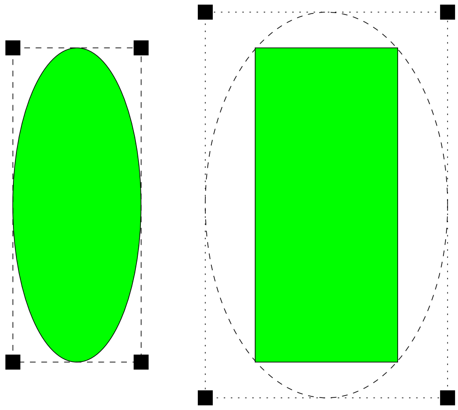


Figure 5.8: Minimum bounding box tasks. The dashed line shows the position of the selection area and the dotted line around the rectangle shows the extension lines that the participant must visualise to correctly place the selection area

pixel, once the mouse button is released. If all four dots do not appear, one of the control points has to be re-acquired and the selection area adjusted accordingly. Whenever a control point is re-acquired by the preferred mouse, the non-preferred mouse automatically gains control of the opposite corner for the bimanual techniques. The red dots are not visible during the sizing of the selection area.

Each participant performed all three techniques in a within-subject design. The technique order was counterbalanced by being rotated for every participant: the first participant performed the task with unimanual, bimanual stretchy, and bimanual toolglass; the second with bimanual stretchy, bimanual toolglass, unimanual; the third with bimanual toolglass, unimanual, bimanual stretchy; and so on.

Before attempting the timed tasks each participant was given a practise run of six tasks with the bimanual toolglass technique. This technique was chosen for the practise tasks as it incorporates all of the skills required to successfully complete the tasks using the other techniques. After these practise tasks, the participant attempted each of the three techniques, first performing two practise tasks and then the eight timed tasks. Each shape to be selected was either a rectangle or an ellipse, and one of four sizes: small

(50x100), medium (130x260), large (200x400) and extra large (280x560). The two practise tasks for each interface were always a 50 x 50 square and a 280 x 280 circle. The order of the eight timed tasks was random. Participants took approximately fifteen minutes to complete all the tasks.

5.3.2 Results

Twelve participants took part in this experiment, all were right handed and very experienced computer users, one out-lier was removed from the results.

The bimanual stretchy technique was the fastest, though not significantly so. The mean task completion times for the unimanual, bimanual stretchy and bimanual toolglass techniques were 12.43 (s.d. 6.08), 11.96 (s.d. 5.53) and 11.29 (s.d. 7.24) seconds respectively (see Figure 5.9). There was no significant difference in these times ($F(2,20)=0.99$, $p=0.39$). As the original minimal bounding box experiment showed that there was a significant difference between the interfaces [39], the performance drop for the bimanual interfaces must be caused by an aspect of the experimental setup. The most likely cause is the poor quality of the non-preferred mouse (H1) combined with the lack of training (H3).

There was a significant difference in the task completion time for the different sizes ($F(3,30)=15.03$, $p=0.00$) with the smaller tasks being completed faster than the larger tasks. (see Figure 5.10). This is to be expected as the larger the shape, the harder the task is. The results also showed significant interactions between interface and shape, and size and shape (see Figures 5.11 and 5.12).

The interface and shape interaction seen in the results is probably caused by the use of poor quality equipment. Prior work has shown that each task has a mechanical component and a cognitive component [39]. The difficulty of the mechanical component for all the tasks is similar, but the difficulty of the cognitive component increases as the difficulty of the task increases. The poor quality of the non-preferred mouse only affects the motor component of each task. As the ellipse is the easier shape to select, the degradation of the motor component has a greater effect than on the rectangle task which has a much larger cognitive component. This finding supports earlier work

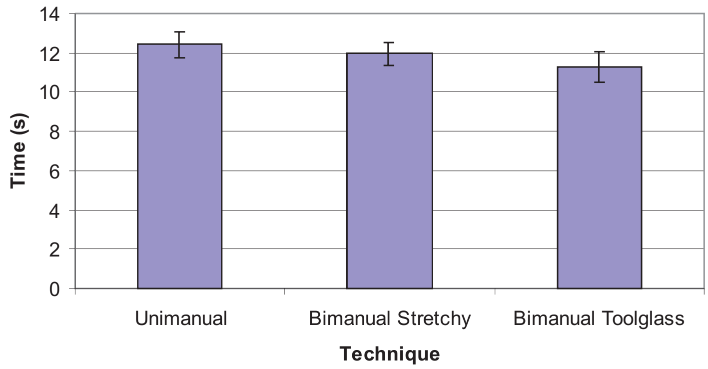


Figure 5.9: Minimum bounding box mean task completion times by technique. Error bars show one standard error above and below the mean.

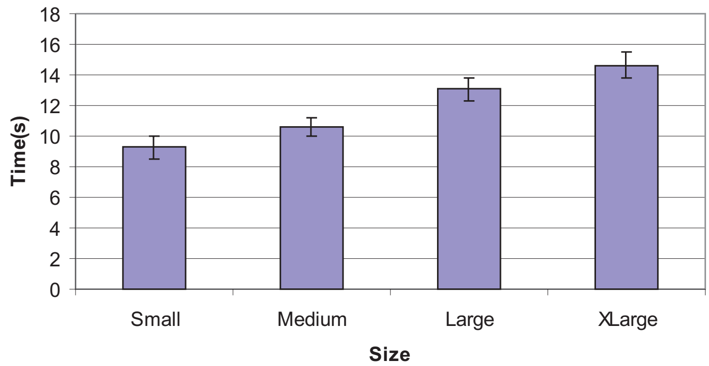


Figure 5.10: Minimum bounding box mean task completion times by size. Error bars show one standard error above and below the mean.

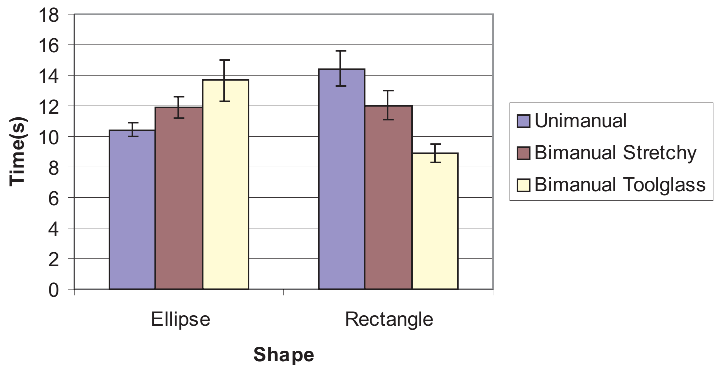


Figure 5.11: Minimum bounding box mean task completion times by technique and shape. Error bars show one standard error above and below the mean.

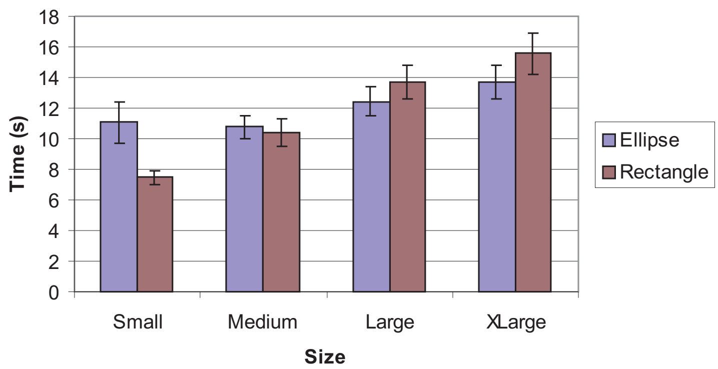


Figure 5.12: Minimum bounding box mean task completion times by size and shape. Error bars show one standard error above and below the mean.

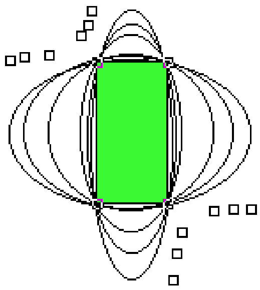


Figure 5.13: Possible solutions for rectangle selection task and control points for selection areas.

[39] stating that bimanual interaction provides cognitive as well as motor benefits.

The interaction between size and shape indicates that the rectangle task rapidly becomes more difficult than the ellipse task. This does not explain why the small rectangle task was faster than the small ellipse task. The way in which the experiment was implemented meant that each of the rectangle tasks had more than one solution. Figure 5.13 shows a range of these possible solutions. The control points shown in Figure 5.13 are in an arrangement similar to a hyperbolic graph. The small rectangle has a large range of possible solutions in close proximity. As the task size increases, the areas containing the correct solutions move further away and become relatively smaller. The ellipse task has smaller areas containing correct solutions, but as these areas are always tangential to the top-most, bottom-most, left-most and right-most points of the ellipse, they are easy to find.

It is worth noting that a planned comparison of the completion times for only the selection task for the rectangle shape does show a significant difference in favour of the bimanual interaction techniques (F(2,20)=19.28,p=0.00).

Chapter VI

Conclusion and Further Work

This thesis has presented four principles for the design of bimanual interaction systems. These principles were used to design two systems (Bi-DM and Bi-Draw) which where evaluated in comparison to equivalent unimanual systems. Bi-DM was faster than its unimanual equivalent, but not significantly so. Bi-Draw was significantly slower than its unimanual equivalent. These results disagreed with prior work. Four explanations were proposed: that the poor quality of the non-preferred mouse degraded the performance of the bimanual systems (H1); that accuracy requirement of the tasks was too low (H2); that the amount of training provided was insufficient (H3); and that the implementation of the bimanual systems suffered from subtle flaws (H4). An expert evaluation was run using Bi-Draw and its unimanual equivalent to test H3. Even with long training, the times where similar. This suggested that while training was a factor, other explanations must be considered. A third experiment was conducted to test H1 and H2. This experiment was based on that of Leganchuk, Zhai and Buxton [39]. The results from the third experiment disagreed with the original work. This indicates that the poor quality of the non-preferred mouse (H1) had a greater effect on the results than the low accuracy requirement of the tasks (H2). The poor quality of the non-preferred mouse had a similar effect to lag. Prior research into lag indicates that it can degrade the performance of a system by up to 64% [40]. This accounts for the lack of a significant result between the Data Mountains, but is not quite enough to account for the difference between Bi-Draw and its unimanual equivalent. It is thought that the combination of the lack of training and the poor quality of the non-preferred mouse heavily degraded the performance of the bimanual systems.

Despite the poor quality of the non-preferred mouse and the lack of training, the design principles have not been shown to inhibit or obstruct the development of good bimanual interaction systems though this process is susceptible to subtle flaws.

6.1 Further Work

The four hypotheses proposed to explain the results of our first two experiments need further investigation. Currently there is little consistency between experiments on the amount of training provided to participants. This causes problems similar to our second experiment where we did not provide enough training as there is no consensus in prior work on what sufficient training is. Within the issue of training is the question of whether the non-dominant hand can be trained to the level of the dominant hand for similar tasks.

The effect of the amount of accuracy required to complete a task has not been studied. If bimanual systems are only more efficient when high levels of accuracy are required, then this has serious ramifications for designing bimanual systems. The dominant hand would have to be able to perform all functions of the system in some way, negating most of the benefits of a bimanual design.

Investigating how the type and quality of input device affects the usability and efficiency of the final system is important for moving bimanual systems from research into production. If expensive devices are needed to reap the most benefits then how does the availability of devices effect the design of the system.

Designing and implementing bimanual interfaces is susceptible to many subtle flaws. The effect these small flaws have needs to be studied so that the design and implementation processes can compensate. If these flaws have only a small effect, then they are compensated for by other benefits and could be considered a matter of style. If they deteriorate the performance of bimanual systems by large amounts then there needs to be ways to find and eliminate them.

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